Short-Term Effects of Tree Removal on Infiltration, Runoff, and Erosion in Woodland-Encroached Sagebrush Steppe

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Abstract

Land owners and managers across the western United States are increasingly searching for methods to evaluate and mitigate the effects of woodland encroachment on sagebrush steppe ecosystems. We used small-plot scale (0.5 m^2) rainfall simulations and measures of vegetation, ground cover, and soils to investigate woodland response to tree removal (prescribed fire and mastication) at two late-succession woodlands. We also evaluated the effects of burning on soil water repellency and effectiveness of aggregate stability indices to detect changes in erosion potential. Plots were located in interspaces between tree and shrub canopies and on undercanopy tree and shrub microsites. Erosion from untreated interspaces in the two woodlands differed more than 6-fold, and erosion responses to prescribed burning differed by woodland site. High-intensity rainfall (102 $mm \cdot h^{-1}$) on the less erodible woodland generated amplified runoff and erosion from tree microsites postfire, but erosion (45–75 $g \cdot m^{-2}$) was minor relative to the 3–13-fold fire-induced increase in erosion on tree microsites at the highly erodible site (240–295 $g \cdot m^{-2}$). Burning the highly erodible woodland also generated a 7-fold increase in erosion from shrub microsites (220–230 $g \cdot m^{-2}$) and 280–350 $g \cdot m^{-2}$ erosion from interspaces. High levels of runoff (40–45 mm) and soil erosion (230–275 $g \cdot m^{-2}$) on unburned interspaces at the more erodible site were reduced 4–5-fold (10 mm and 50 $g \cdot m^{-2}$) by masticated tree material. The results demonstrate that similarly degraded conditions at woodland-encroached sites may elicit differing hydrologic and erosion responses to treatment and that treatment decisions should consider inherent site-specific erodibility when evaluating tree-removal alternatives. Strong soil water repellency was detected from 0 cm to 3 cm soil depth underneath unburned tree canopies at both woodlands and its strength was not altered by burning. However, fire removal of litter exacerbated repellency effects on infiltration, runoff generation, and erosion. The aggregate stability index method detected differences in relative soil stability between areas underneath trees and in the intercanopy at both sites, but failed to provide any indication of between-site differences in erodibility or the effects of burning on soil erosion potential.

Key Words: aggregate stability, hydrophobicity, juniper, piñon, prescribed fire, rangeland, restoration, soil water repellency, tree mastication

INTRODUCTION

Ecological restoration of woodland-encroached sagebrush steppe is a primary concern for land owners and management agencies in the western United States. Piñon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodlands now occupy approximately 18 million ha of rangeland in the Intermountain West (Miller and Tausch 2001), much of which was historically sagebrush steppe (Davies et al. 2011; Miller et al. 2011). Range expansion of piñon and juniper conifers in the western United States has been attributed to multiple exogenous forces including climate variability, land use, decreased fire frequency, and CO_2 fertilization (Miller and Wigand 1994; Miller and Rose 1995; Knapp and Soule 1996; Miller and Tausch 2001; Miller et al. 2005, 2008; Romme et al. 2009). The ecological impacts of woodland encroachment vary across the diverse domain in which piñon and juniper have encroached, but include decreased shrub and herbaceous cover; reduced habitat for key sagebrush obligate fauna; increased bare ground, surface runoff, and soil erosion; and a decline in ecosystem productivity and goods and services (Connelly et al. 2000; Miller et al. 2000; Aldrich et al. 2005; Miller et al. 2005; Pierson et al. 2007, 2010; Davies et al. 2011; Miller et al. 2011). Postencroachment restoration strategies commonly aim to recruit sagebrush vegetation and thereby improve site resistance and resilience to woodland encroachment (Miller et al. 2005; Davies et al. 2011; Williams et al. 2014). Resistance refers to the persistence of abiotic and biotic characteristics of a site that dictate community-sustaining ecological processes whereas resilience refers to the recovery of these attributes following disturbance (Miller et al. 2013; Chambers et al. 2014). Well vegetated sagebrush rangelands trap water and nutrient-rich soil resources (Pierson et al. 1994, 2007) that propagate plant productivity and further enhance

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ecosystem structure and function (e.g., Wilcox et al. 2003; Ludwig et al. 2005; Puigdefábregas 2005). This ecohydrologic feedback is thought to increase site resistance to plant invasions and resilience of ecosystem structure and function (Briske et al. 2008; Turnbull et al. 2012; Williams et al. 2014).

Sagebrush plant community responses to tree-removal are strongly related to the pretreatment plant community and site conditions, treatment method, the prevailing soil temperature and moisture regimes, and posttreatment weather trends (Miller et al. 2013). Woodland encroachment into sagebrush steppe occurs in three phases: 1) phase I: tree cover (<1 to 3 m height) expands, but shrubs and herbaceous species remain the dominant cover; 2) phase II: tree cover increases to 10–50%, shrub and herbaceous cover decline, and trees influence key ecological processes; and 3) phase III: tree cover stabilizes, becomes the dominant cover type ($>75\%$ shrub mortality), and exerts the primary control on ecological processes (Miller et al. 2000, 2005, 2008; Johnson and Miller 2006). Sagebrush steppe restoration on late phase II to phase III woodlands (late-succession) can be difficult due to limited understory propagules and seed (Koniak and Everett 1982; Miller et al. 2000, 2005). Fires in late succession woodlands commonly burn at high severity, consume nearly 100% of sagebrush and herbaceous cover, reduce the surface soil seed bank, and cause extensive tree mortality. High severity burns that remove key native perennial species decrease resistance to weed invasions, particularly on sites with mesic-aridic soil temperature-moisture regimes ($>8°C$ annual temperature and <305 mm annual precipitation) (Young and Evans 1978; Melgoza et al. 1990; Koniak 1985; Chambers et al. 2007; Condon et al. 2011). Sagebrush does not resprout following burning and can require as long as 20 to more than 50 yr to recover postfire (Barney and Frischknecht 1974; Miller and Heyerdahl 2008; Ziegenhagen and Miller 2009). Fire surrogate treatments (e.g., mechanical tree mastication and cutting) can reduce shrub and herbaceous treatment-related mortality, but often leave residual juvenile piñon and juniper (Miller et al. 2013). Residual trees can dominate a site within as little as 15 to 60 yr following mechanical tree removal (Miller et al. 2005, 2013). Bates et al. (2006, 2007, 2011) suggested that posttreatment recruitment of desired perennial species is most likely where pretreatment perennial grass and forb densities are at least 1–2 and 5 plants per square meter respectively. The posttreatment vegetation response is also influenced by precipitation trends and can exhibit significant temporal variability due to oscillating wet/dry years regardless of pretreatment composition (West and Yorks 2002; Bates et al. 2007). Recent syntheses by Miller et al. (2005, 2013) suggest successful restoration of woodland-encroached sagebrush steppe is most likely on frigid-xeric sites and when tree-removal is applied early in the encroachment gradient (phase I–II). However, much of the woodland domain across the Intermountain West exists in aridic as well as xeric climates and is approaching late succession (Miller and Tausch 2001; Miller et al. 2008).

Knowledge regarding linkages in vegetation and hydrologic responses to the various tree removal treatments is limited. The general premise is that favorable canopy and ground cover recruitment following tree removal will reduce runoff and erosion and enhance site productivity. Amplified soil loss from late-succession woodlands occurs primarily due to interconnected runoff source areas on degraded surface soils (Davenport et al. 1998; Pierson et al. 2007, 2010, 2013; Williams et al. 2014). Poor infiltration in bare interspaces (area between tree and shrub canopies) promotes runoff generation that concentrates into high-velocity flow paths through the intercanopy. The high-velocity flow incises degraded surface soils and becomes the primary conduit for downslope movement of rainsplash- and flow-detached sediment during runoff events (Pierson et al. 2010; Al-Hamdan et al. 2012a; Williams et al. 2014). Pierson et al. (2007) found that enhanced intercanopy herbaceous cover 10 yr following tree cutting in a western juniper (*J. occidentalis* Hook.) woodland significantly reduced runoff generation and soil erosion from simulated rainfall. The study measured negligible soil loss from simulated storms (55 $mm \cdot h^{-1}$, 60 min, 32.5 m^2 plots) in well-vegetated intercanopy areas of the cut woodland and 118 $g \cdot m^{-2}$ soil erosion from simulations in the uncut woodland. Overland flow simulations in the study produced 15-fold more erosion from the uncut than cut site. Pierson et al. (2007) attributed the higher rates of soil loss at the uncut woodland to formation of concentrated flow within the bare intercanopy. Cline et al. (2010) found placement of masticated tree material in bare interspaces of a Utah juniper (*J. osteosperma* [Torr.] Little) woodland improved infiltration of artificial rainfall (102 $mm \cdot h^{-1}$, 45 min, 0.5 m^2 plots) by 3-fold and resulted in an 8-fold decrease in soil erosion. Williams et al. (2014) found burning generated a 35-fold increase in erosion from simulated high-intensity rainfall (102 $mm \cdot h^{-1}$, 45 min, 0.5 m^2 plots) in tree canopy areas of a western juniper woodland 1 yr postfire. However, runoff from a lower intensity simulated storm (64 $mm \cdot h^{-1}$, 45 min, 0.5 m^2 plots) and erosion from overland flow simulations (15–45 $L \cdot min^{-1}$, 8 min) were both significantly reduced (2- to nearly 15-fold) 2 yr following burning of intercanopy areas at the study site. The intercanopy represented approximately 74% of the study area. Williams et al. (2014) attributed the improved intercanopy hydrologic function to fire-induced increases in herbaceous vegetation and suggested that burning may provide an ecohydrologic restoration pathway for woodland-encroached sagebrush steppe where fire promotes intercanopy herbaceous production.

Rangeland managers and policymakers are increasingly relying on rapid field assessment protocols, ecological (e.g., state-and-transition models) models, and predictive technologies to prioritize and evaluate the need for restoration treatments, as well as to quantify posttreatment improvements in rangeland health (Pyke et al. 2002; Briske et al. 2008; Weltz et al. 2008; Petersen et al. 2009; Herrick et al. 2010). The quality of these approaches depends in part on knowledge of key indicator variables to measure and the ability of selected conceptual and quantitative models to accurately predict ecosystem processes of interest. Rangeland management agencies and researchers in the United States have sought to improve and standardize protocols for assessing rangeland health (Pyke et al. 2002; Herrick et al. 2010) and now include physical process-based ecological information in conceptual and quantitative models (e.g., Petersen et al. 2009; Nearing et al. 2011; Al-Hamdan et al. 2012b). Although these efforts have advanced assessment approaches, identification of indicator variables is often undertaken without well-replicated quantification of the processes that they are inferred to drive. This is particularly true relative to woodland encroachment and